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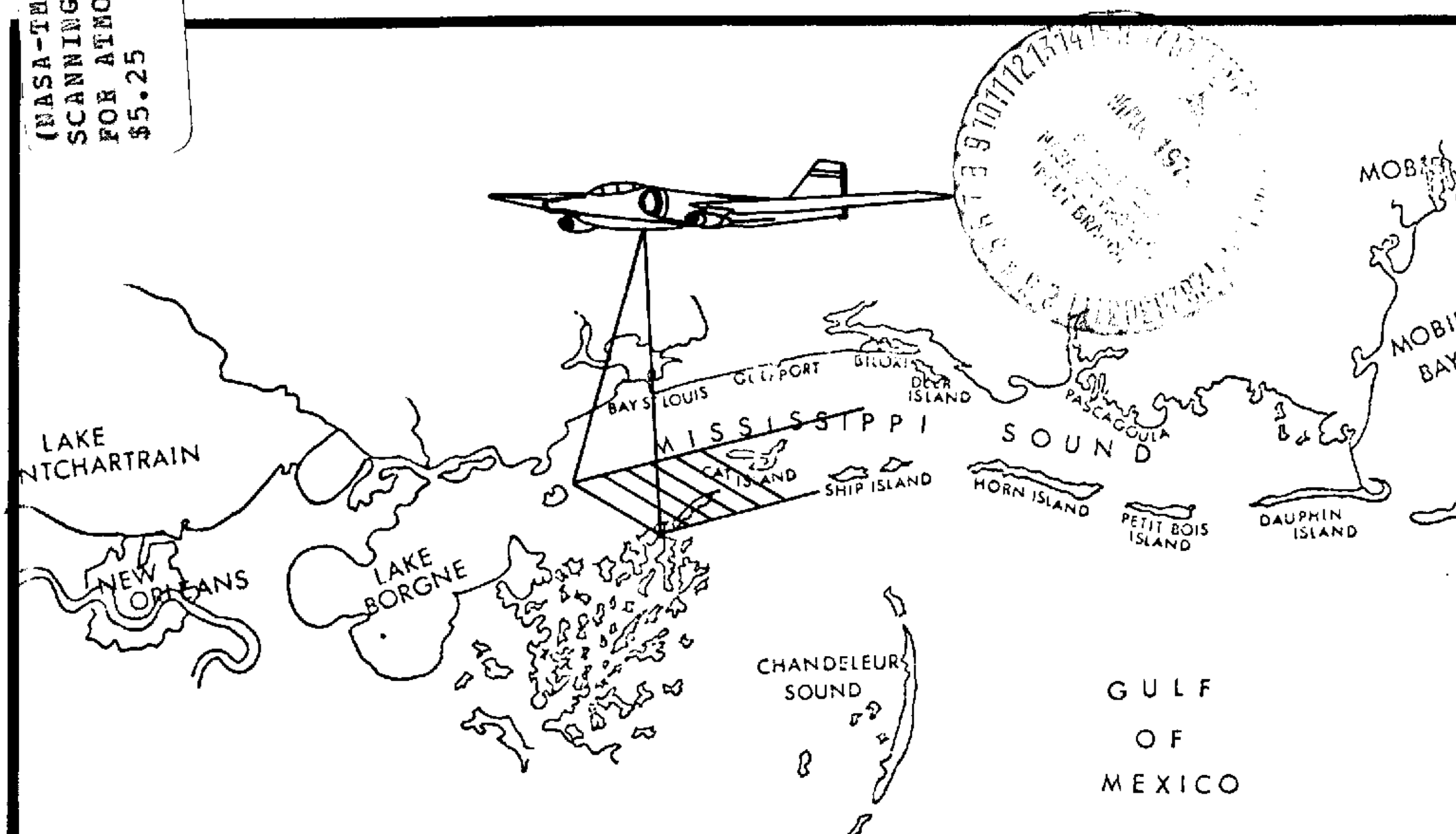
CORRECTING AIRBORNE SCANNING INFRARED RADIOMETER MEASUREMENTS FOR ATMOSPHERIC EFFECTS

by

Robert D. Boudreau

September 1972



MANNED SPACECRAFT CENTER

Report No. 029

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Principal Investigator

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ACKNOWLEDGMENTS

This study was initiated in response to a need expressed by Mr. E.L. Tilton, III, for developing an improved technique for determining sea surface temperature from the RS-18 scanning radiometer. Mr. James Halbach of the Lockheed Electronics Company did the programing of the radiation model used in the study and assisted in the preparation of the figures. Mr. Barney Congdon of the Lockheed Electronics Company drafted the figures and the front cover. Miss Becky Prevou typed the manuscript.

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ABSTRACT

The methods for correcting scanning infrared radiometer measurements of sea temperature for atmospheric effects are reviewed. Two techniques are developed for determining atmospheric corrections from observations made by a scanning radiometer. Both techniques depend on knowing the radiometer's limb function, i.e., the characteristics of the apparent change in surface temperature due to the longer atmospheric path encountered as the scan angle departs from nadir. The limb function for an RS-18 scanning radiometer is derived from calculations made with a radiation model and used to demonstrate the techniques. One technique requires observations made over an isothermal water surface within the area being remotely sensed. The other technique does not depend on an isothermal water surface but requires a boat measurement of radiometric sea surface temperature within the area being remotely sensed. The radiation model used to derive the limb function does not account for the effects of atmospheric particulates on the correction. It is hypothesized that the effect of particulates on the limb function derived in this study is negligible, and therefore the technique essentially obtains the total correction. The techniques developed here can be used over land provided that a section of isothermal land exists within the experiment area or that a radiometric measurement of surface temperature is made at the surface.

INTRODUCTION

Scanning infrared radiometers are being used aboard aircraft to determine sea surface temperature patterns (e.g., Atwell, 1972; Boudreau, 1972a; Thomann, 1972). Since temperature normally decreases with height in the atmosphere, the effect of absorption and emission of radiation by atmospheric constituents is to cause the surface temperature as measured by the radiometer to be lower than the actual surface temperature. Moreover, a scanning radiometer views the sea surface through longer atmospheric paths as the angle from nadir at which it views the surface is increased. The influence of the atmosphere is greater as the angle of the radiometer increases and causes the measured temperature of an isothermal sea surface to decrease with increasing angle. This apparent lowering of surface temperature with increasing angle is termed limb darkening; viz., on a positive infrared image, an isothermal surface appears darker (colder) toward the limb (horizon) of the earth.

Limb darkening occurs when atmospheric temperature decreases with height. Limb brightening, an isothermal surface appearing lighter (warmer) toward the horizon of the earth, can occur if a temperature inversion exists above the surface and the scanning radiometer is observing the surface from within the temperature inversion layer.

In order to ascertain the sea surface temperature pattern from scanning radiometer imagery, the data must be corrected for these atmospheric effects. For that purpose a radiation model (Boudreau, 1972b) has been developed which calculates the atmospheric corrections in the infrared due to absorption and emission by water vapor and carbon dioxide, the principal radiating gases in the atmosphere. The model is incomplete, however, because it does not as yet include the effect of aerosols on radiative transfer in the atmosphere (Cole, et al., 1972; Herman, 1972). If the aerosol particles are assumed to be homogeneous in composition and spherical in shape, their radiative characteristics are prescribed by Mie theory and can be incorporated in the model in the manner developed by Harlan (1972). The model would still have two main shortcomings, however. First, with the exception of water droplets, aerosol particles are not spherical (Kim and Yarger, 1972), and second, the model would require the particle size distribution and index of refraction be specified as a function of altitude. Remote sensing systems do not as yet have the capability for determining the particles' size, distribution and index of refraction.

The above difficulties have led investigators to develop empirical techniques for determining atmospheric corrections. Saunders (1967a) developed for a non-scanning radiometer a correction technique which was based on viewing the sea surface at 0° and 60° from a low (300m) flying aircraft. For determining the correction, Saunders' technique requires that the viewed sea surface be at the same temperature, a condition which is likely to be met from a low flying aircraft. A scanning radiometer views the sea surface at a continuum of angles within the limits of its scan. Hence, it would seem that the additional information obtained from a scanning radiometer on the apparent change in sea surface temperature would enable one to improve upon Saunders' method and develop a more general technique for determining the atmospheric correction. The purpose of this report is to examine the extent to which the atmospheric correction can be determined from scanning radiometer observations made from aircraft.

DEVELOPMENT

General. The apparent surface temperature, $T(0)$ and $T(\theta)$, measured by a scanning radiometer at scan angles of 0 and θ, respectively, can be expressed as

$$T(0) = T(S,0) - \Delta T(0), \tag{1}$$

and

$$T(\theta) = T(S,\theta) - \Delta T(\theta), \tag{2}$$

where $T(S,0)$ and $T(S,\theta)$ are the surface temperatures of the sea which would be measured by the radiometer if no atmosphere were present at point 0 and θ, respectively, and $\Delta T(0)$ and $\Delta T(\theta)$ are the atmospheric corrections at scan angles of zero and θ, respectively. In (1) and (2), it is assumed that the sea radiates as a blackbody. Eqs. (1) and (2) contain four unknowns: $T(S,0)$, $T(S,\theta)$, $\Delta T(0)$ and $\Delta T(\theta)$. Our goal is to solve this system of equations for the atmospheric corrections, $\Delta T(0)$ and $\Delta T(\theta)$. This system of two equations with four unknowns is not amenable to solution. We shall attempt to develop techniques for reducing the number of unknowns. The addition of another equation for an observation made at another scan angle, θ', does not make a system of three tractable equations because two additional unknowns, $T(S,\theta')$ and $\Delta T(\theta')$, are introduced.

If observations of $T(S,0)$ and $T(S,\theta)$ were made from two boats at points viewed from 0 and θ, Eqs. (1) and (2) could be solved for $\Delta T(0)$ and $\Delta T(\theta)$. One of the boats could be eliminated if a portion of water of uniform surface temperature could be located for calibration purposes. For an isothermal sea surface, (1) and (2) become

$$T(0) = T(S) = \Delta T(0) \tag{3}$$

$$T(\theta) = T(S) - \Delta T(\theta), \tag{4}$$

and with the boat observation of T(S) the equations can be solved for the atmospheric corrections. Note that since θ is arbitrary, the system of equations will yield the atmospheric correction for all angles.

The most desirable scheme for determining atmospheric corrections is one which dispenses with the dependence upon boat observation. Toward that end, let us express the atmospheric correction, $\Delta T(\theta)$, as a function of T(0) modified by a limb function, $[1 + F(\theta)]$; i.e.,

$$\Delta T(\theta) = T(0)\,[1 + F(\theta)]. \tag{5}$$

The choice of this functional form for the limb function will become apparent later in the development. The use of (5)in (4) enables the set of equations to be written as

$$T(0) = T(S) - \Delta T(0) \tag{6}$$

$$T(\theta) = T(S) - \Delta T(0)\,[1 + F(\theta)]. \tag{7}$$

Assuming for the moment that the form of $F(\theta)$ can be determined by numerical modeling or from experimental data, we can solve (6) and (7) for $\Delta T(0)$ and T(S), viz.,

$$\Delta T(0) = [T(0) - T(\theta)]/F(\theta) \tag{8}$$

$$T(S) = T(0) + \Delta T(0). \tag{9}$$

Thus if $F(\theta)$ is known, any scan of the radiometer of water with a uniform surface temperature can be used to determine the atmospheric correction. It is not difficult to identify in the scanning radiometer data water which has a uniform surface temperature because the apparent temperature, $T(\theta)$, will be symmetric about, $T(0)$; i.e., $T(-\theta) = T(\theta)$ as shown in Figure 1. This symmetry of $T(\theta)$ will be true provided that there are no horizontal variations in atmospheric correction and no symmetrical variations in water temperature, which is unlikely. For the horizontal distances (at most 30 miles from 60,000 ft.) viewed by an airborne scanning radiometer, the horizontal variations in the atmosphere over water usually can be considered to have a negligible effect on the atmospheric correction. This condition of horizontal homogeniety in the atmosphere is especially well approximated during the conditions which will permit remote sensing of the sea surface, i.e., clear skies at and below flight altitude. The greater the altitude from which the scanning radiometer views the surface, the smaller is the likelyhood of horizontal homogeniety, e.g., atmospheric homogeniety is rarely observed in the broad (2,000 mi.) field of view of scanning radiometers on the NOAA meteorological satellites.

If water at a uniform surface temperature cannot be found, then (6) and (7) become

$$T(0) = T(S,0) - \Delta T(0) \tag{10}$$

$$T(\theta) = T(S,\theta) - \Delta T(0)\,[1 + F(\theta)], \tag{11}$$

which can still be solved for $\Delta T(0)$ from radiometer data taken when a boat which is measuring either $T(S,0)$ or $T(S,\theta)$ is in the scanning radiometer's view and its position in the scan is known.

The atmospheric correction established by these techniques would be applicable over an area which had the same atmospheric structure as

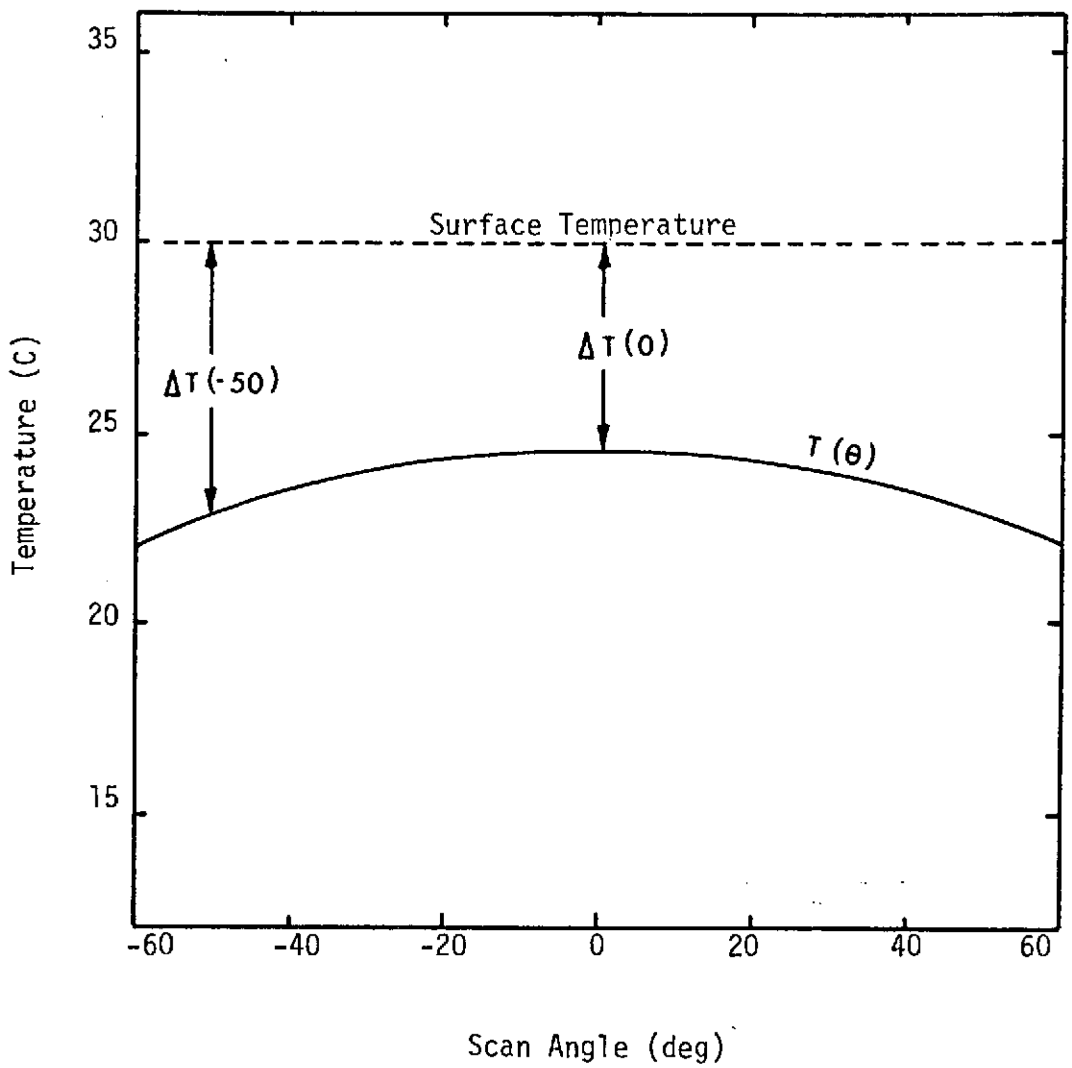

Fig. 1. Example of temperature (solid line) as measured by scanning radiometer at 10,000 ft. over a 30°C isothermal sea surface (dashed line).

that which existed above the line where the correction was determined. If, in the atmosphere over the area being remotely sensed, horizontal gradients exist which significantly effect the magnitude of the atmospheric correction, then the techniques would have to be applied in as many different locations in the area as is necessary to determine the changes in correction over the area. If only a single correction were applied in a situation where in fact a change in correction occurred, the result would be to superimpose a fictitious temperature gradient on the actual surface temperature field.

Limb function. $F(\theta)$ can be determined from observations made over an isothermal sea surface provided there is a boat measurement of $T(S)$. Under these conditions by (6) and (7)

$$F(\theta) = [T(0) - T(\theta)]/[T(S) - T(0)]. \tag{12}$$

In keeping with the aim of developing a technique that eliminates, if possible, the need for boat measurement, we shall investigate the behavior of $F(\theta)$ by numerical modeling.

A radiation model for calculating atmospheric corrections (Boudreau, 1972b) was used to compute $\Delta T(\theta)$ for a variety of atmospheric conditions likely to be encountered over the unfrozen sea. Seven model atmospheres used previously by Boudreau (1972b) and six radiosonde observations which were made along the northern coast of the Gulf of Mexico during actual remote sensing experiments were used to calculate corrections for an RS-18 scanning radiometer. These model atmospheres and soundings are presented as Figures 1A - 13A in the Appendix and are referred to in the text by numbers which correspond to their figure number, e.g., atmosphere 13 is represented in Fig. 13A.

Atmospheric corrections are a function of the spectral response function of a radiometer and as such are specific to each radiometer (Boudreau, 1972b). Corrections were calculated for the RS-18 because it is being used extensively for sea temperature mapping by the NASA Earth Resources Laboratory along the northern coast of the Gulf of Mexico.

The RS-18 was built to the NASA Earth Resources Laboratory's specifications by Texas Instruments Inc. and has a total scanning angle of 100°, i.e., 50° to right and left (-50°) of nadir. The RS-18 is flown on a twin-engine Beechcraft which has an operating ceiling of 10,000 ft; its spectral response function is shown in Fig. 2.

The results of the calculations of $\Delta T(\theta)$for 3,000, 5,000 and 10,000 ft. altitudes are given in Figs. 3, 4, and 5, respectively. Note that all the curves exhibit limb darkening except 13 which was calculated for an atmosphere whose lowest 6,000 ft. was warmer than the underlying surface. The curves in these Figs. illustrate that the atmospheric correction increases for longer atmospheric paths which are encountered as a result of increasing altitude or scan angle. The data in Figs. 3-5 also indicate that the amount of limb darkening or brightening is proportional to $\Delta T(0)$, e.g.,

$$\Delta T(60) - \Delta T(0) = F\Delta T(0). \tag{13}$$

A graph of $\Delta T(60) - \Delta T(0)$ vs. $\Delta T(0)$ was made for the purpose of determining the validity of (13). This graph is presented as Fig. 6 and shows that a straight line of slope 0.64 can be fitted to the data with a standard error of 0.04°C, which is well within the noise equivalent error of 0.2°C for the RS-18. That the amount of limb darkening can be expressed by as simple a relation as (13) is a welcome finding. At the

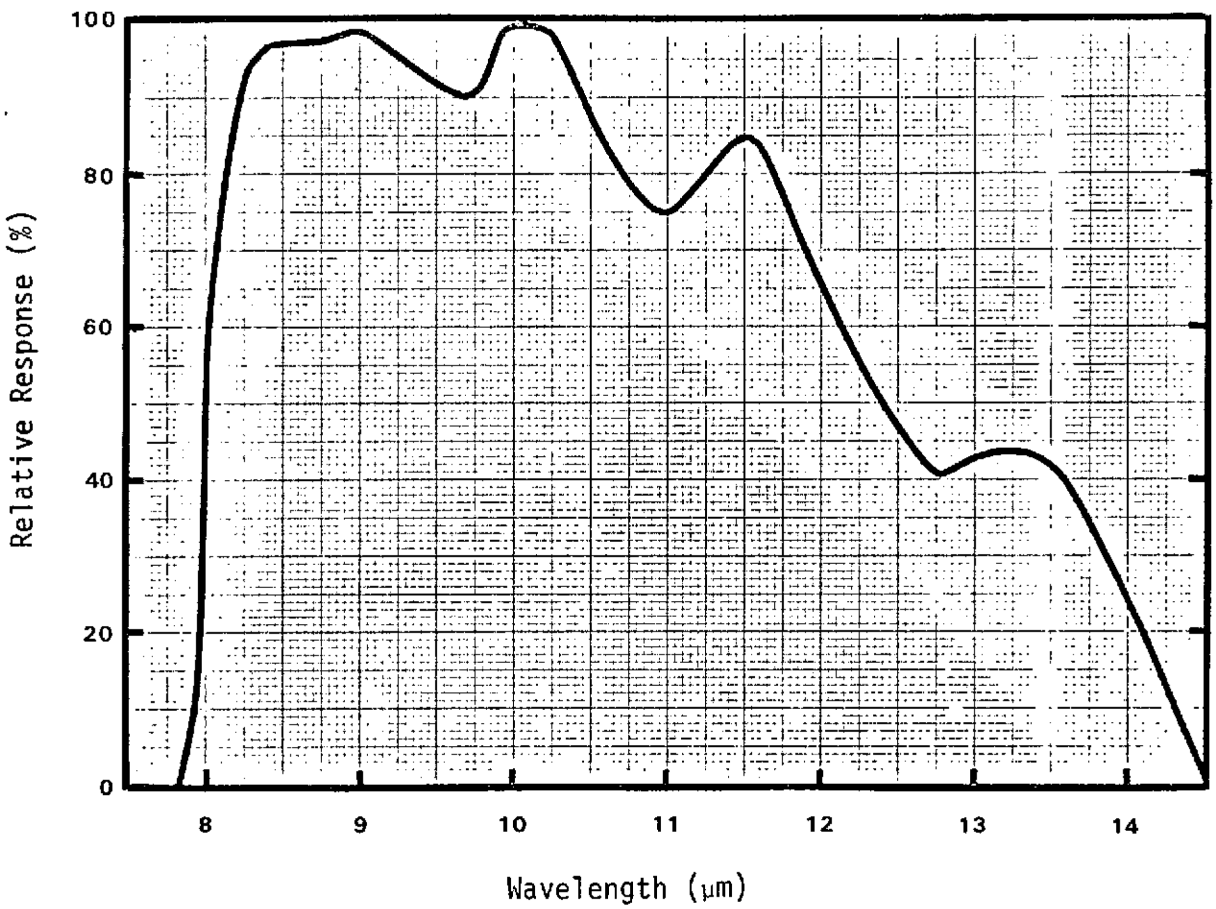

Fig. 2. Spectral response of the RS-18 scanning radiometer.

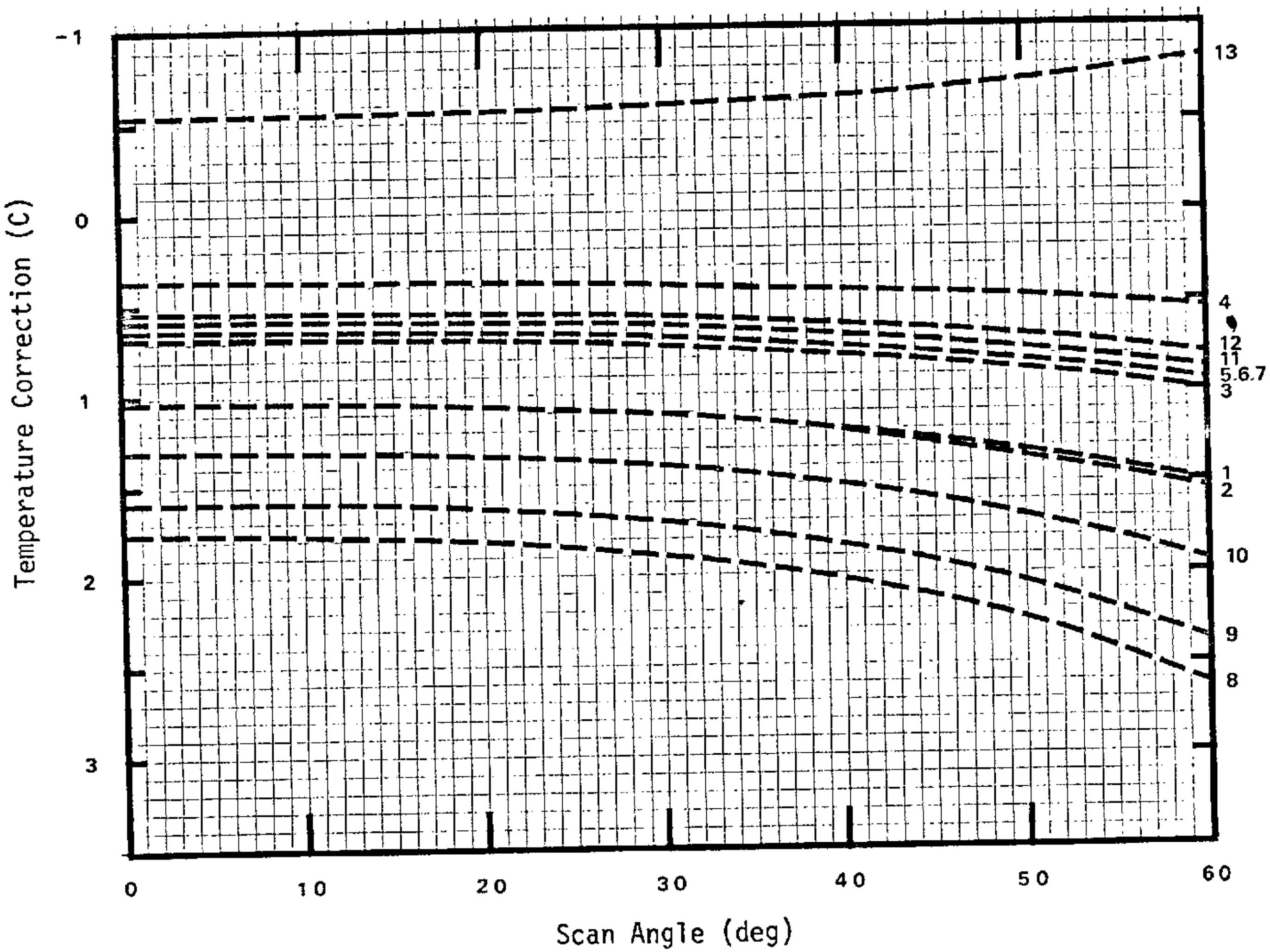

Fig. 3. Calculated atmospheric corrections vs. scan angle for RS-18 radiometer at 3,000 ft. Number labels of curves correspond to atmospheres shown in Appendix.

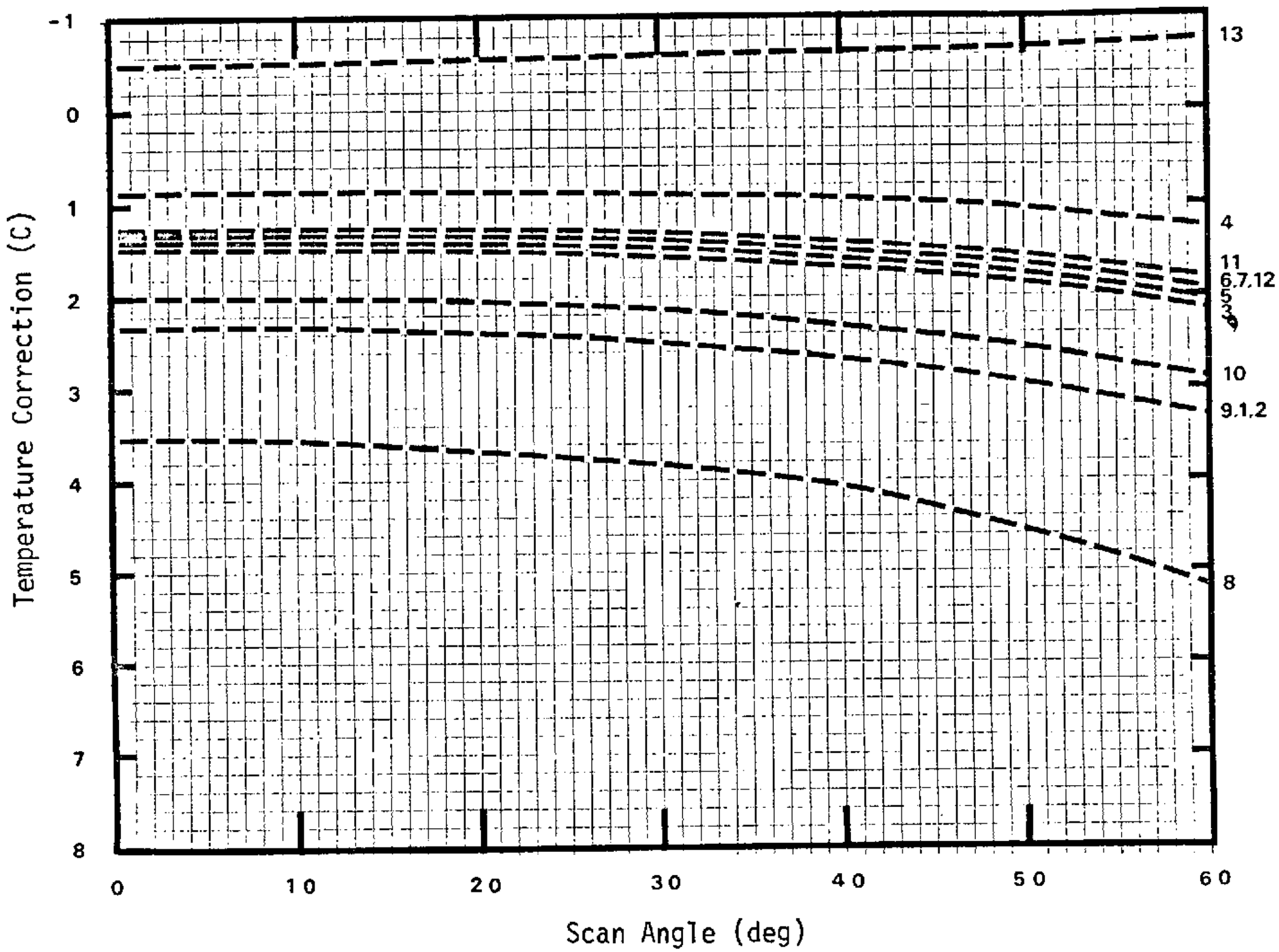

Fig. 4. Calculated atmospheric corrections vs. scan angle for RS-18 radiometer at 5,000 ft. Number labels of curves correspond to atmospheres shown in Appendix.

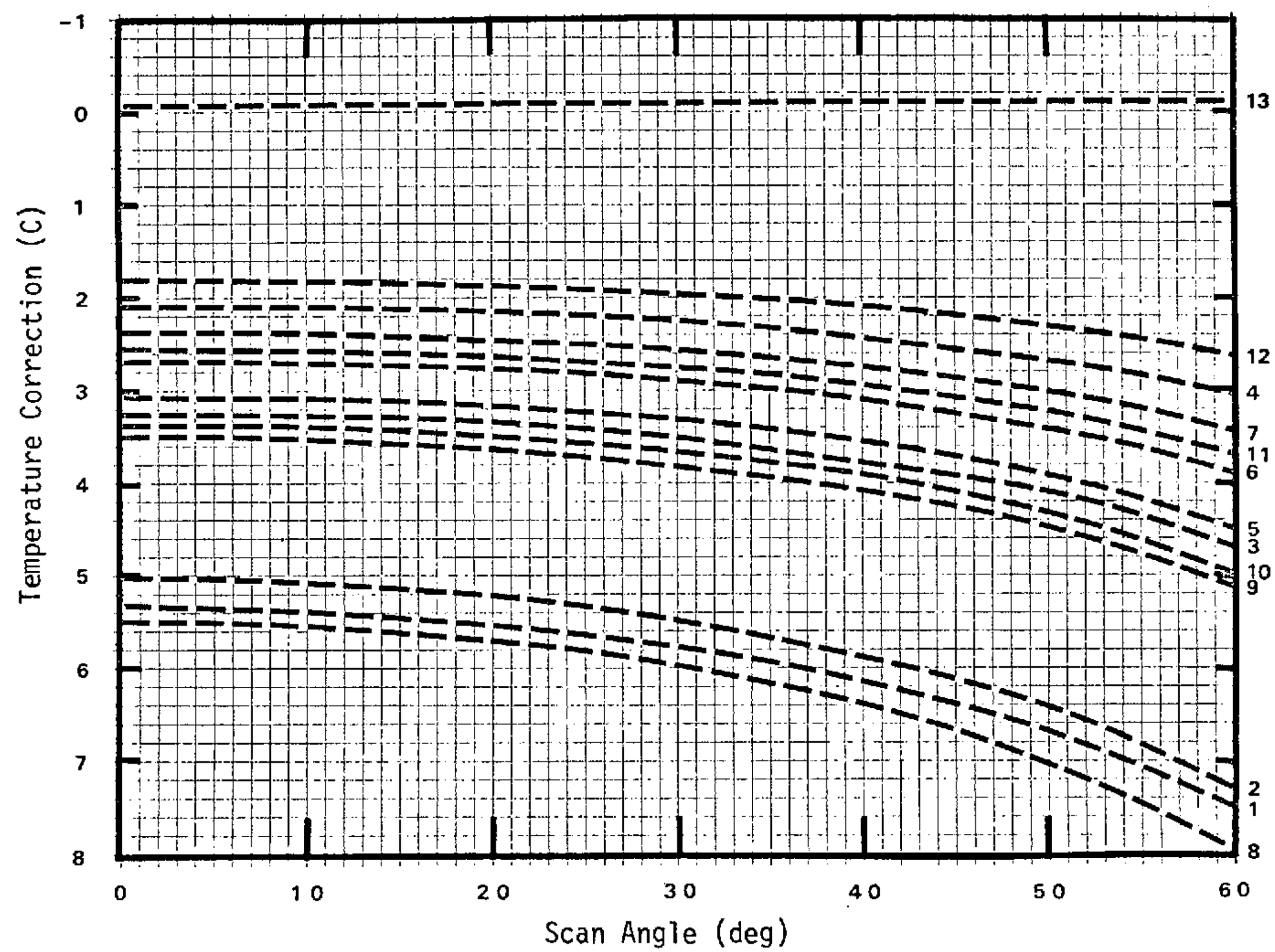

Fig. 5. Calculated atmospheric correction vs. scan angle for RS-18 radiometer at 10,000 ft. Number labels of curves correspond to atmospheres shown in Appendix.

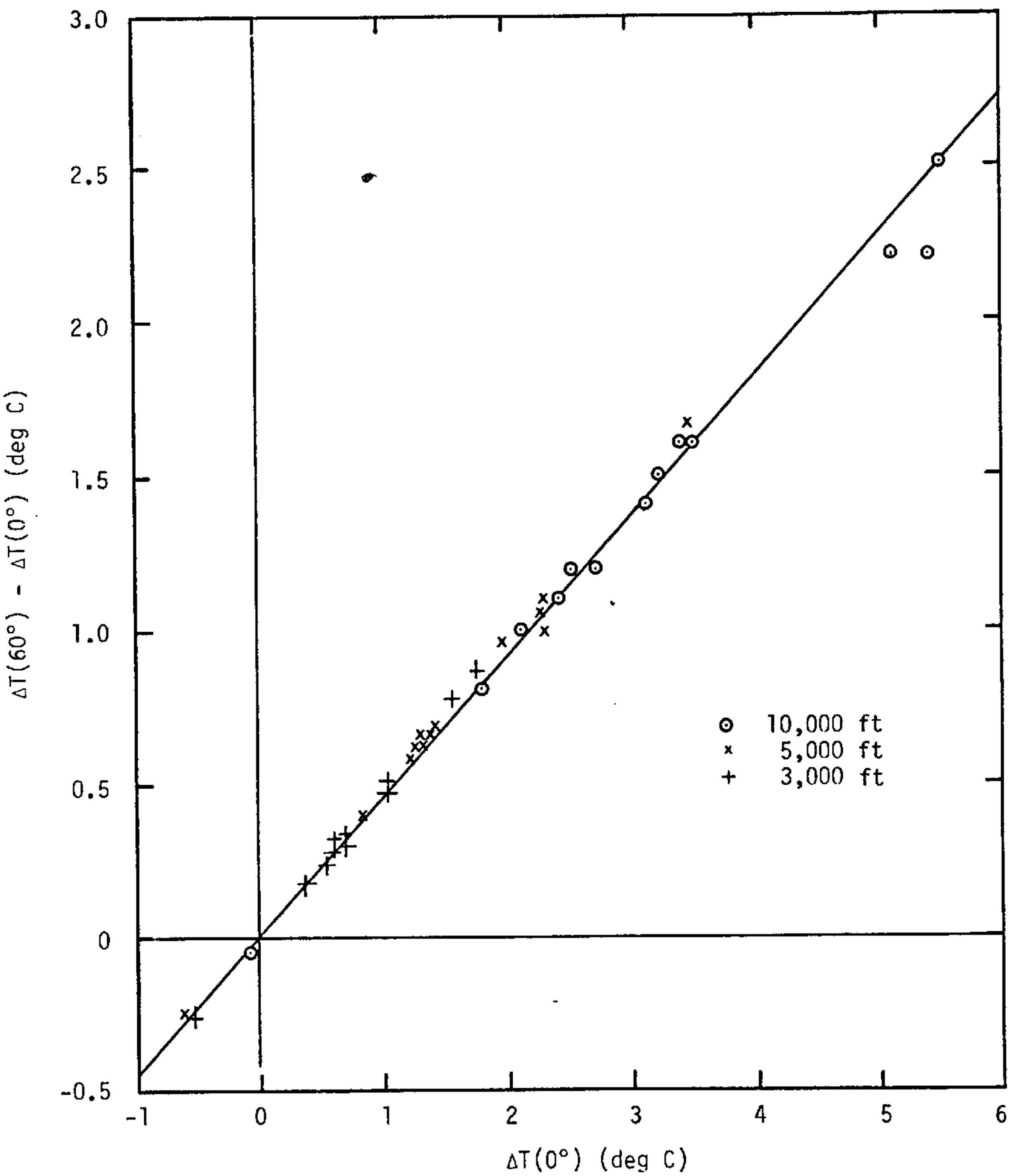

Fig. 6. Calculated atmospheric correction at 60° minus correction at 0° vs. correction at 0° for the RS-18 radiometer.

outset, it was thought that the limb function might be a function of altitude and mean temperature and humidity in the air layer below the aircraft. Obviously, the major effects of all these variables is accounted for by $\Delta T(0)$.

In light of the preceeding, it appears that a generalized form of (13) will be suitable for describing the limb phenomenon,

$$\Delta T(\theta) - \Delta T(0) = F(\theta)\ \Delta T(0), \tag{14}$$

from which we obtain (5), i.e.,

$$\Delta T(\theta) = \Delta T(0)\ [1 + F(\theta)]. \tag{15}$$

Experimentation with several types of functions yielded

$$F(\theta) = \alpha\theta^{\beta} \tag{16}$$

as a suitable form for the limb function. In (16), θ is in degrees, $\alpha = 0.1605\text{x}10^{-4}$, and $\beta = 2.5$. The standard error of estimate of $\Delta T(\theta)$ given by (15) with (16) is less than 0.1 deg C. A comparison of $\Delta T(\theta)$ given by (15) and $\Delta T(\theta)$ for atmospheres 8 and 11 at 10,000 ft. and atmosphere 13 at 3,000 ft. is given in Table 1.

Experimental verification. A limb function has been developed for the RS-18 radiometer which will allow determination of the atmospheric correction from data taken over an isothermal water surface. This limb function is based on calculations made with a radiation model that described radiation by water vapor and carbon dioxide only. The model does not account for the radiative effects of particulate matter, which exist in the real atmosphere. It is hypothesized here that the effect of atmospheric correction due to particulates will be mainly to increase

Table 1. Atmospheric corrections for the RS-18 radiometer calculated by Eq. (15) and by the radiation model for atmospheres 8 and 11 at 10,000 ft. and atmosphere 13 at 3,000 ft.

Scan Angle (deg)	Temperature Correction (deg C)					
	Atmosphere 8		Atmosphere 11		Atmosphere 13	
	Eq. 15	Model	Eq. 15	Model	Eq. 15	Model
0	5.52	5.52	2.54	2.54	-0.53	-0.53
15	5.60	5.63	2.58	2.60	-0.54	-0.54
30	5.95	5.98	2.74	2.76	-0.57	-0.57
45	6.72	6.69	3.09	3.09	-0.64	-0.65
60	7.99	7.99	3.68	3.70	-0.77	-0.78

$\Delta T(0)$ and that its effect on $F(\theta)$ will be negligible. In order to test this hypothesis, a comparison of $F(\theta)$ given by (16) with $F(\theta)$ as determined experimentally by (12) should be made.

Unfortunately, experimental data for making such a comparison do not exist at present. RS-18 data have been taken over a quasi-isothermal sea with a boat making ground truth measurements, but the boats made measurements of surface temperature by means of a dipping bucket. These measurements are representative of the temperature at several centimeters below the surface. Due to heat transfer by molecular means between ocean air, there usually exists a sharp temperature gradient in the upper few millimeters of the sea (Boudreau, 1964, Saunders, 1967b). Since $T(S)$ is the effective radiating temperature of the top 0.1 mm of the sea, a temperature difference $\Delta T'$, usually exists between $T(S)$ and bucket temperature, $T(B)$, i.e.,

$$T(S) = T(B) - \Delta T'. \tag{17}$$

Boudreau (1964) and Saunders (1967b) have found that $\Delta T'$ is a variable whose sign and magnitude depend on the amount of heat being lost or gained by the sea. In the Gulf of Mexico and Caribbean Boudreau found that $\Delta T'$ ranged from -0.4 to 1.7 deg C with the average of all observations being 0.6 deg C.

Substitution for $T(S)$ from (17) into (12) gives

$$F(\theta) = [T(0) - T(\theta)]/[T(B) - \Delta T' - T(0)], \tag{18}$$

which indicates that our attempt to verify $F(\theta)$ using bucket temperature observations would be biased by $\Delta T'$. At 10,000 ft. in a humid atmosphere (e.g., atmosphere 8), a $\Delta T' = 0.6C$ would cause $F(60°)$ to be 10 percent below its true value if $T(B)$ were used in place of $T(S)$ in (12). For the purpose of testing our hypothesis that $F(\theta)$ as determined in this study will not be appreciably altered by atmospheric particulates, a series of experiments will be undertaken in which a boat making observations of $T(S)$ with a radiation thermometer will be overflown with the RS-18. The results of these experiments will be reported at a later date, as well as a study of the effects of non-blackbody emission by the sea.

The existence of $\Delta T'$ does not affect our technique for determining atmospheric correction, $\Delta T(0)$, because (8) is still obtained when $T(S)$ from (17) is substituted into (6) and (7), i.e.,

$$T(0) = T(B) - \Delta T' - \Delta T(0) \tag{19}$$

$$T(\theta) = T(B) - \Delta T' - \Delta T(0)[1 + F(\theta)]. \tag{20}$$

In fact, after this technique is used to establish $\Delta T(0)$, (19) can be used to determine $\Delta T'$ when the radiometer is flown over a boat which is measuring $T(B)$.

Another difficulty which has been encountered using the RS-18 is the existence of a fictitious temperature gradient in the observation. This phenomena is sometimes referred to as a "ramp" and appears to be due to failure at times of the gyromechanism to keep the RS-18 level. The presence of a ramp in the data will complicate the atmospheric correction technique by making it difficult to find isothermal water. The difficulty can be overcome, however, as follows. If the water surface is suspected (from previous observation) of being isothermal but does not appear so on the oscilloscope presentation of the data, i.e., $T(\theta) \neq T(-\theta)$, the flight line should be flown again but in the opposite direction. Let us designate the data taken when flying the line in the reverse direction as $T^*(\theta)$. If there is no ramp but a gradient of sea temperature, $T^*(\theta) = T(-\theta)$. If a ramp exists in the data but no gradient in sea temperature, $T^*(\theta) = T(\theta)$. Moreover, the ramp can be eliminated from the data and the resulting data used to determine atmospheric corrections.

SUMMARY

In essence, two techniques have been developed in this study for determining atmospheric corrections from scanning infrared radiometer data. Both techniques utilize the limb function which has been derived here from calculations made for an RS-18 radiometer with a radiation model which does not account for atmospheric particulates. The first technique requires that observations be made of a section of the sea which has a uniform surface temperature. The second technique does not depend on observing an isothermal sea but requires that a radiometer observation of sea surface temperature be made from a boat or other platform.

It is hypothesized that the effect of atmospheric particulates on the limb function will be negligible. This hypothesis can not be tested from previously collected data because boat measurements of surface temperature have been made by bucket sampling rather than by radiometer. Future remote sensing experiments will include a radiation thermometer determination of surface temperature so that the limb function hypothesis may be tested.

The emphasis in this study has been with the development of techniques for deriving atmospheric corrections from scanning radiometer measurements made over water. However, the two techniques developed here can be used with measurements made over land provided the requirements of the techniques are satisfied, i.e., either some land at uniform temperature must be observed or a radiometric observation of surface temperature be made at the surface. Admittedly, it may be more difficult to find isothermal land than isothermal water due to variations in soil, vegetation, surface slope, etc.

APPENDIX

MODEL ATMOSPHERES

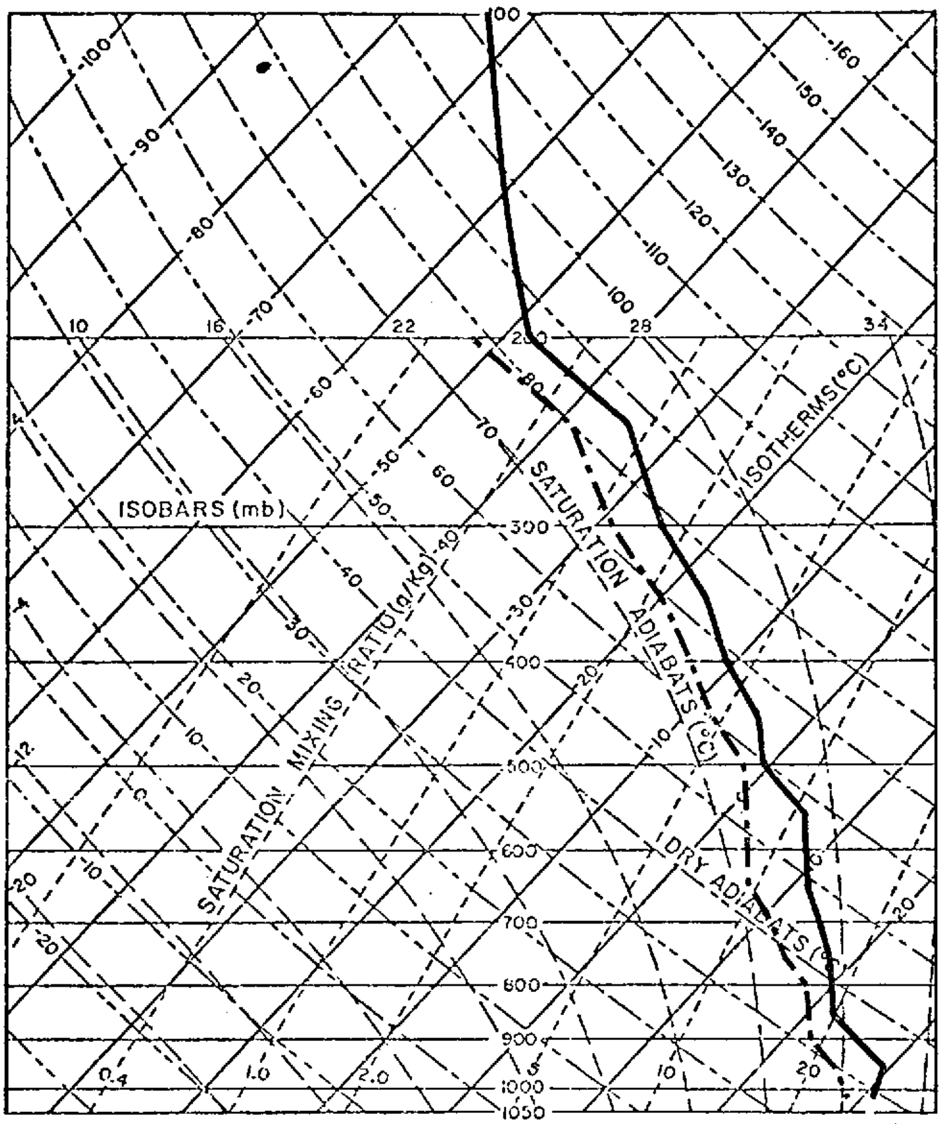

Fig. 1A. Vertical distribution of temperature (solid line) and dew point (dashed line) for Model #1 - Tropical Storm.

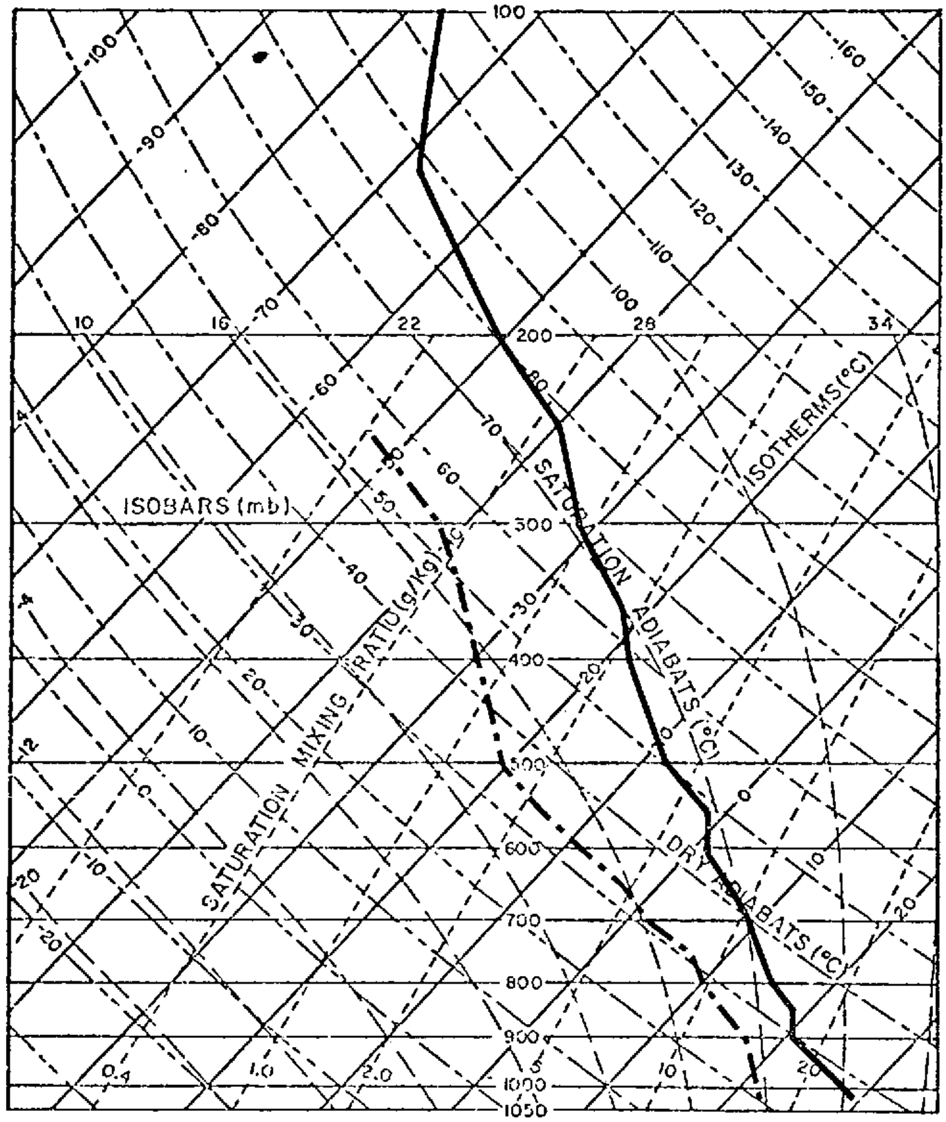

Fig. 2A. Vertical distribution of temperature (solid line) and dew point (dashed line) for Model #2 - Sub-tropical Summer.

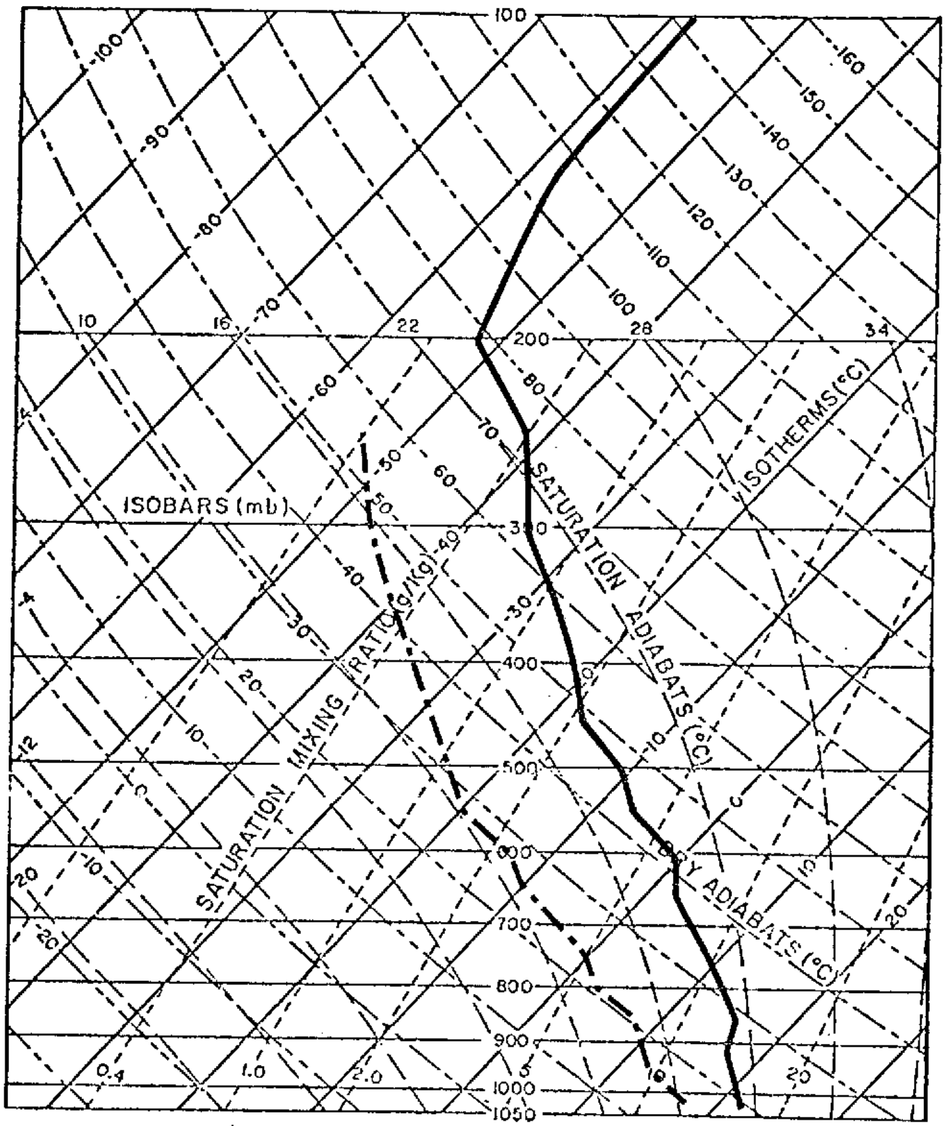

Fig. 3A. Vertical distribution of temperature (solid line) and dew point (dashed line) for Model #3 - Mid-latitude Summer

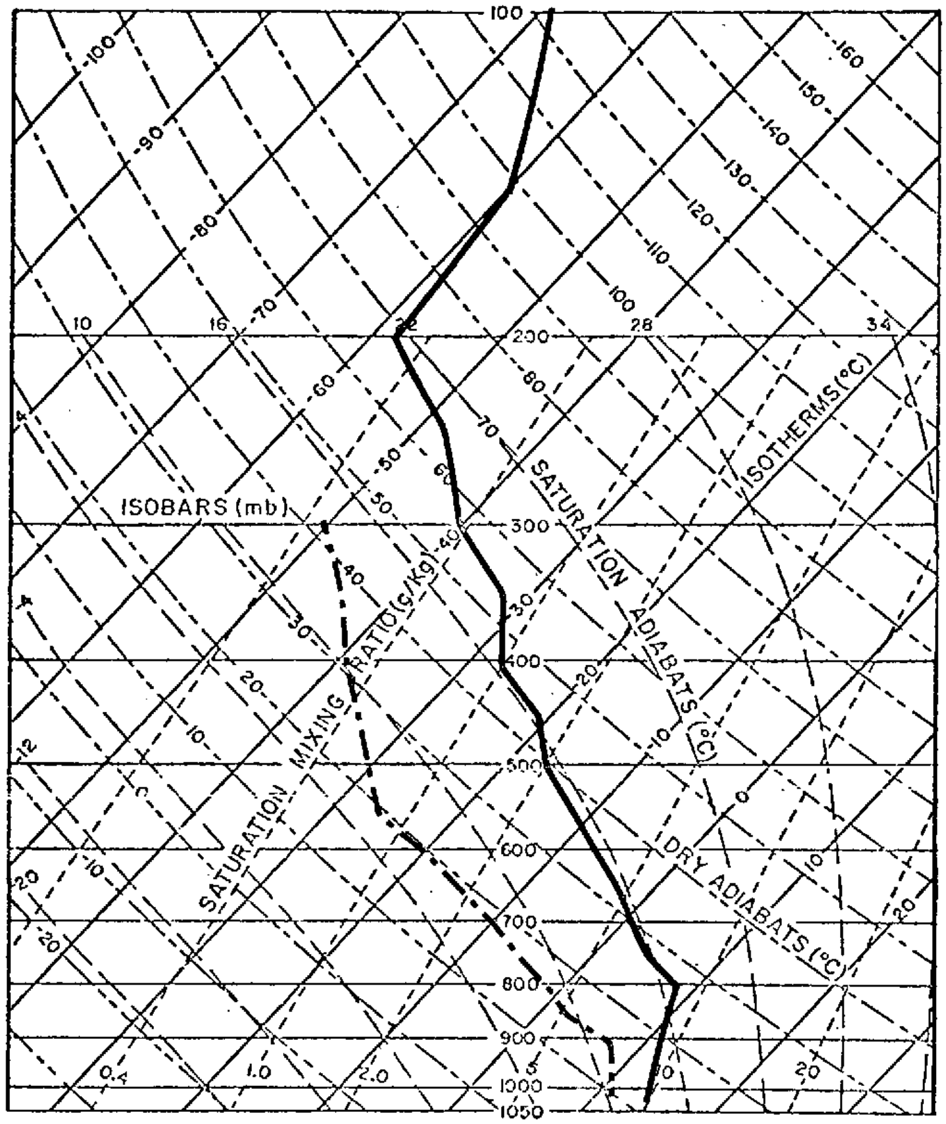

Fig. 4A. Vertical distribution of temperature (solid line) and dew point (dashed line) for Model #4 - Sub-tropical Winter.

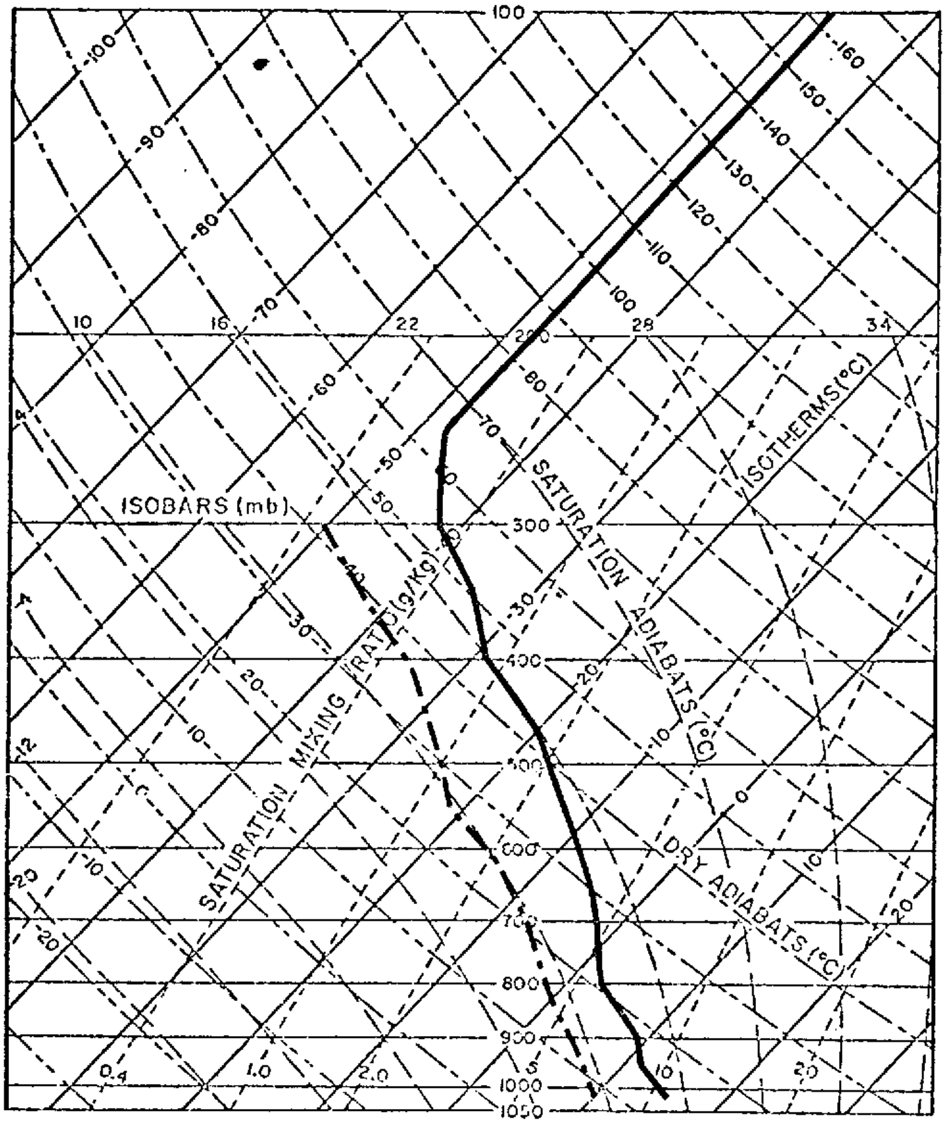

Fig. 5A. Vertical distribution of temperature (solid line) and dew point (dashed line) for Model #5 - Sub-arctic Summer.

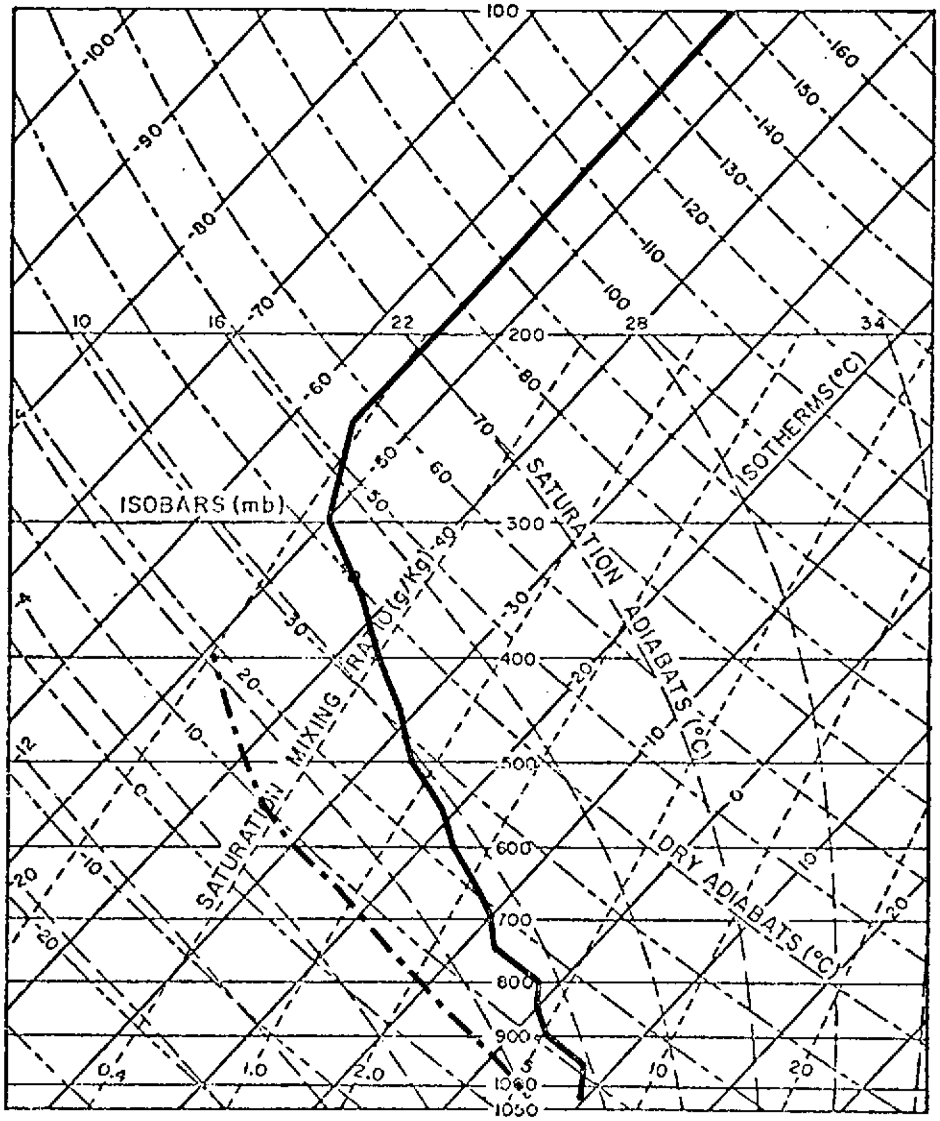

Fig. 6A. Vertical distribution of temperature (solid line) and dew point (dashed line) for Model #6 - Maritime Polar.

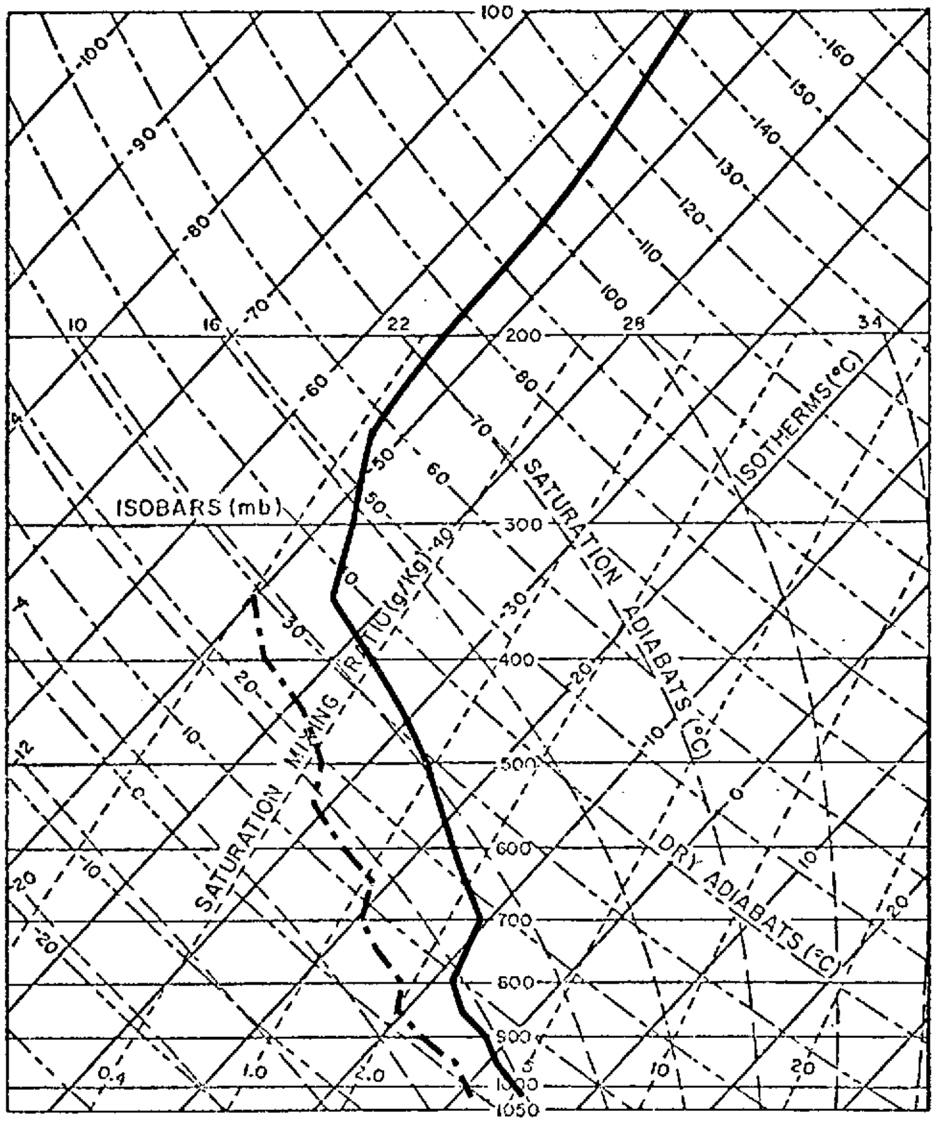

Fig. 7A. Vertical distribution of temperature (solid line) and dew point (dashed line) for Model #7 - Mid-latitude Winter.

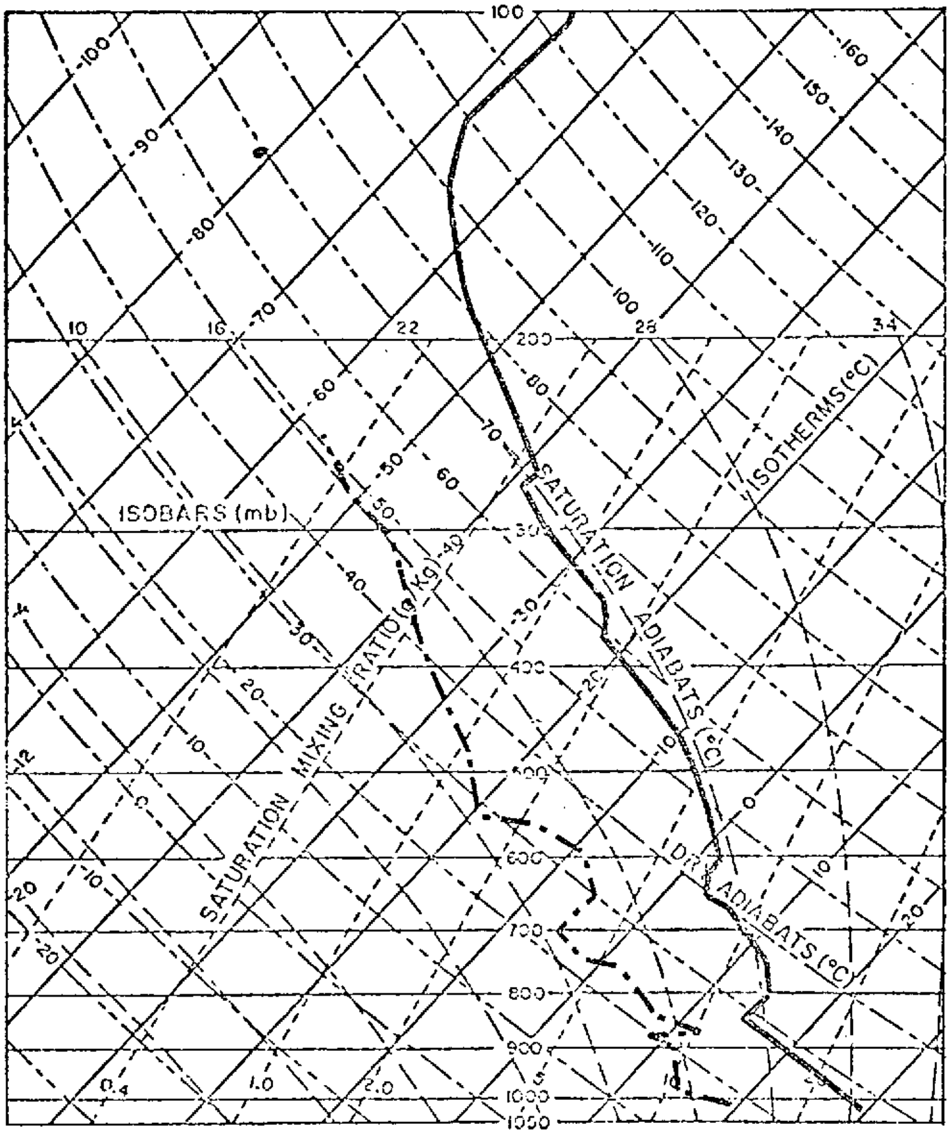

Fig. 8A. Mississippi Test Facility, Radiosonde, 1630 GMT, 22 July 1971, plotted on a skew T-log P diagram. Temperature (solid line) and dew point (dashed line).

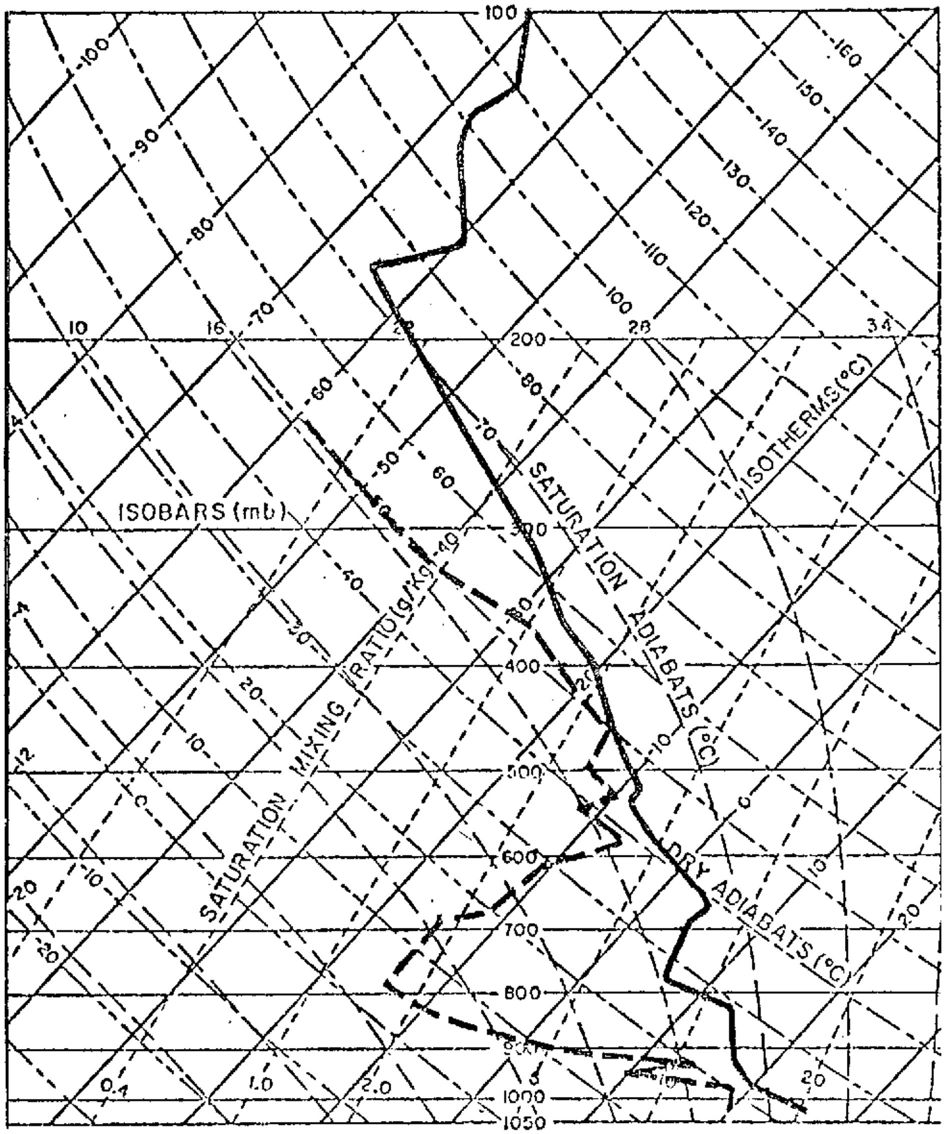

Fig. 9A. Boothville, Louisiana, Radiosonde, 1630 GMT, 2 May 1972, plotted on a skew T-log P diagram. Temperature (solid line) and dew point (dashed line).

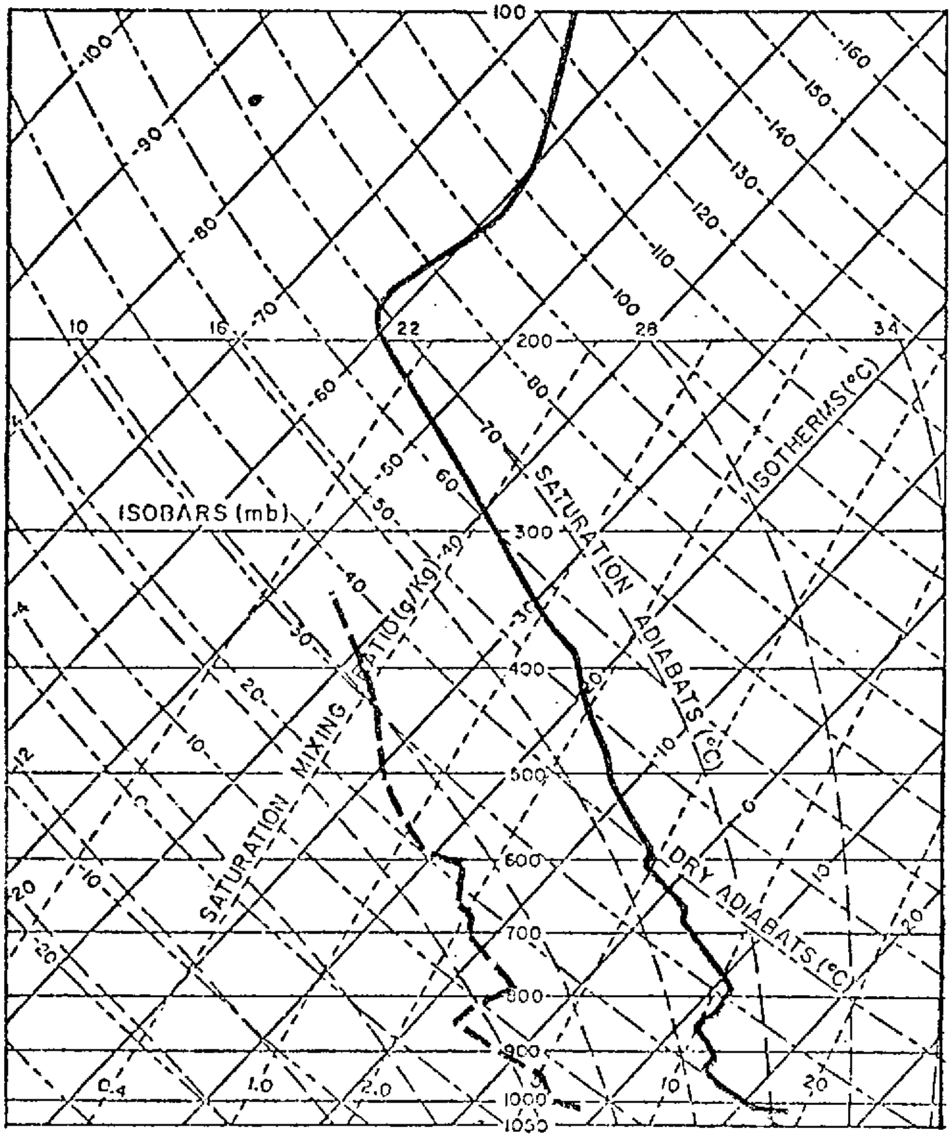

Fig.10A. Mississippi Test Facility, Radiosonde, 1500 GMT, 5 May 1972, plotted on a skew T-log P diagram. Temperature (solid line) and dew point (dashed line).

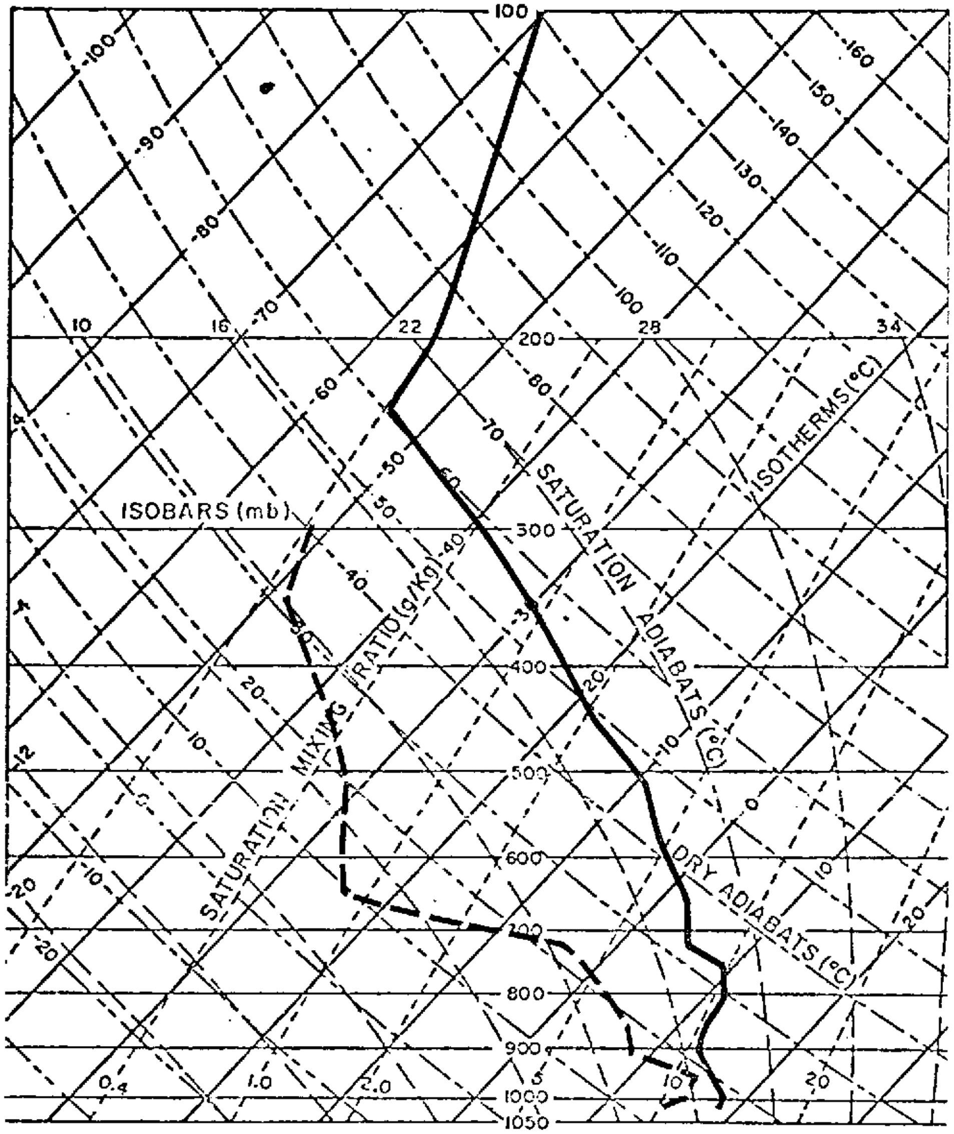

Fig.11A. Boothville, Louisiana, Radiosonde, 1700 GMT, 26 January 1972, plotted on a skew T-log P diagram. Temperature (solid line) and dew point (dashed line).

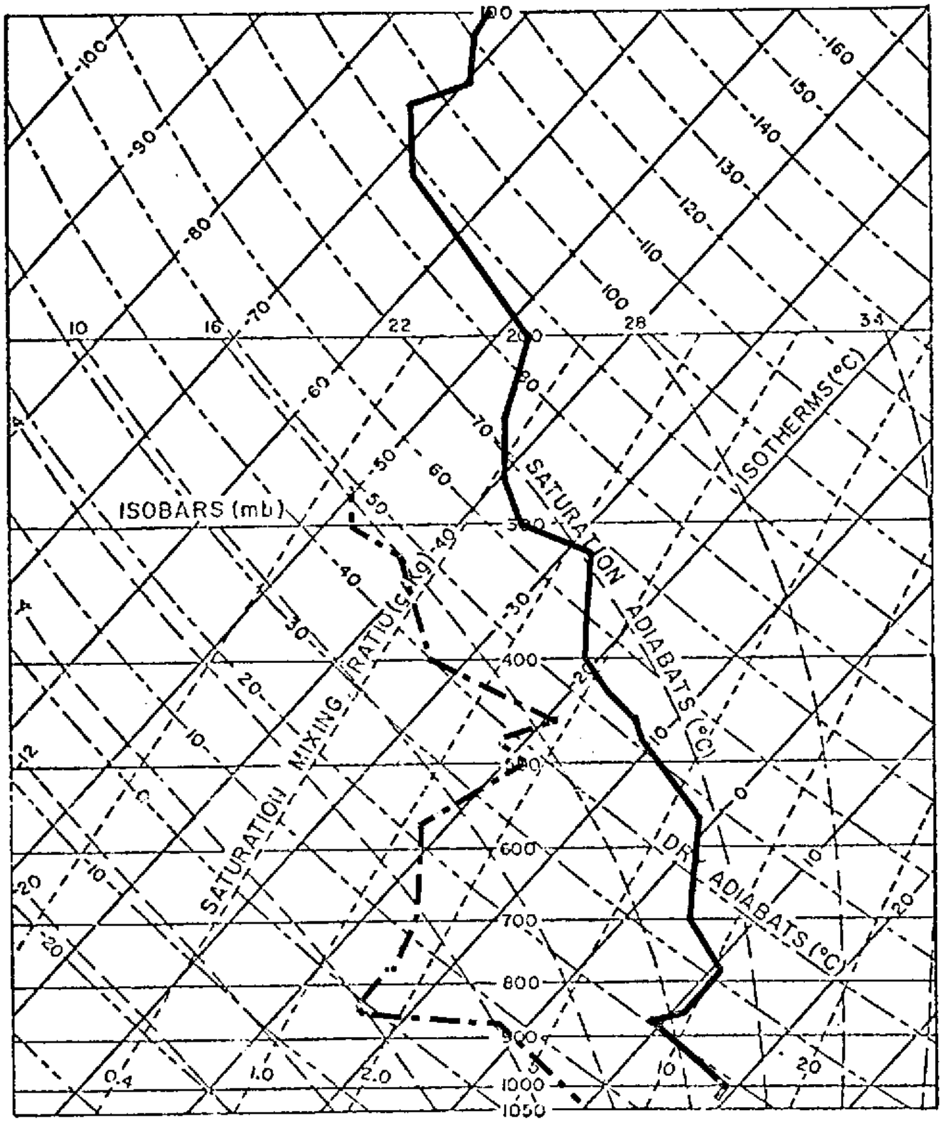

Fig.12A. Boothville, Louisiana, Radiosonde, 2300 GMT, 21 November 1971, plotted on a skew T-log P diagram. Temperature (solid line) and dew point (dashed line).

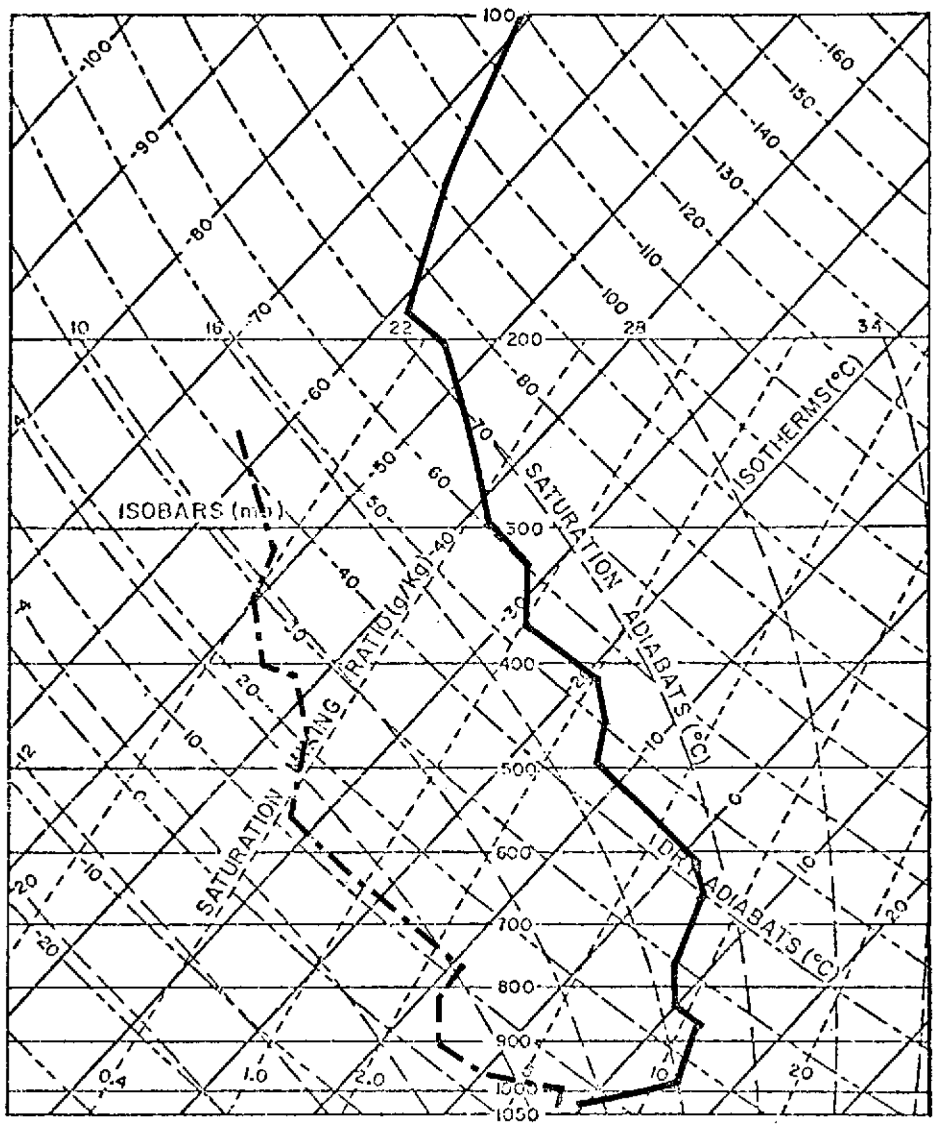

Fig.13A. Eglin AFB, Florida, 1115 GMT 21 November 1971 radiosonde. Temperature (solid line) dew point (dashed line).

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